“Evaluation and Characterization of In-Line Annealed Continuous Cast Aluminum Sheet ”
Annual Project Report
(DE-FC07-01ID14024)

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Project Title: Evaluation and Characterization of In-Line Annealed Continuous Cast Aluminum Sheet

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Laboratory: Oak Ridge National Laboratory, Oak Ridge, TN 37831

Award Number: DE-FC07-01ID14024

Subcontractors: University of Kentucky
University of Michigan
Oak Ridge National Laboratory

Other Partners: Commonwealth Aluminum
Ajax Magnathermic

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Project Objective: The goal of this project is to develop optimized, energy-efficient thermo-mechanical processing procedures for in-line annealing of continuously cast hot bands of two 5000 series aluminum alloys (5754 and 5052). The implementation of the R&D will result in the production of sheet with improved formability at high levels of productivity, consistency, and quality.

The proposed R&D involves the following efforts:

- Design and build continuous in-line annealing equipment for plant-scale trials
- Carry out plant-scale trials at Commonwealth Aluminum Corp.'s (CAC) plant
- Determine the effects of processing variables on the microstructure, texture, mechanical properties, and formability of aluminum sheet
- Optimize the processing variables utilizing a metallurgical model for the kinetics of microstructure and texture evolution during thermo-mechanical processing
- Develop design parameters for commercial implementation
- Conduct techno-economic studies of the recommended process equipment to identify impacts on production costs

Background: In the first year of the project, the microstructural features and mechanical properties of AA5754 and AA5052 were characterized using hot bands that were annealed off-line. The mechanical properties were also characterized after cold deformation and annealing of the hot bands. Modeling the hot deformation showed excess effective plastic strain at the surface than in the midthickness, that resulted in faster recrystallization kinetics / finer grain size in the surface that was confirmed by rapid anneal experiments using the IR heating facilities at ORNL. It was shown that in order to anneal the hot band in-line in a period of 1-2 seconds, a specific outlet temperature was required. Rapid heating resulted in a grain size that was significantly smaller than the conventional furnace anneal or salt-bath anneals. Microstructure modeling of the recrystallization process was initiated using a Monte Carlo technique using the hot band microstructures characterized by EBSP.

In the second year an online induction heating system was designed, built and installed at the Commonwealth Aluminum continuous casting facility. Plant trials of in-line annealing of 5754 and 5052 hot bands were completed successfully. The in-line annealed samples are being evaluated.

Status:

1. **Formability studies (University of Michigan)**

The forming limit diagrams for in line annealed material was determined and compared with that of HB material annealed under normal conditions for one alloy system. The results obtained were positive. It was observed that in inline annealing improves formabiltity but too high a temperature of annealing does not help and is observed to reduce formability. It is believed that variations in the type of recrystallization may not play a big role in formability as long as recovery and recrystallization effects have removed the cold work sufficiently.

It has been demonstrated that cold rolling followed by recrystalization improves forming limit of 5052 Al up to a thickness of 0.063", but below this thickness forming limit is adversely affected.

It has been found that higher degrees of cold rolling increases the amount of retained deformation texture in this material even after the normal recrystallization step. Please check the intensities of Cube texture (200) that decreases with increasing cold rolling reduction from 0.125" to 0.063" down to 0.030". On the other hand, the (111) intensities increase with increasing reduction. Thus under similar annealing conditions, the degree of recrystallization varies in these alloys possibly due to particle pinning. Since recrystallization involves migration of grain boundaries, it is believed that inadequate migration of grain boundaries can also leave damage to particle-matrix interfaces produced during rolling. Such damaged interfaces would then lead to void initiation during forming of the sheet and lower the forming limit. We find this the case for sheets rolled to 0.030".

Voids generated at particles are compared for two thickness. It is clear that for a lower level of strain the void density is lower. The 0.030” material shows more voids than the 0.063” thick sheet. We believe that this problem eventually reduces the biaxial formability of 5052 Al at the 0.030” gauge. It would then be conceivable that a higher annealing temperature or a longer annealing time might overcome the problems associated with the thinner gauge. It should be noted that optical micrographs are inadequate to show these problems within the material, and SEM must be used to see these voids.

2. Evaluation of Mechanical properties and microstructure (University of Kentucky/Secat Inc)

The sheets produced during the continuous in line annealing trials have been evaluated for tensile properties, microstructure, and earing measurement. The results obtained are found to be comparable to the values obtained via the normal route. Based on the results obtained further work is going on to determine the optimum temperatures for in line anneal and cold work properties. Further studies are to be carried out on formability along with hole expansion measurements.

FLD studies and hole expansion show encouraging results and work is proceeding to correlate the results between in line and conventional anneal.

3. Analytical Modeling of Recrystallization Kinetics (ORNL)

1. Mechanical Testing (ORNL)

A total of sixteen plate specimens of 5754 aluminum were annealed with high intensity plasma lamps and tested in tension at room temperature. Yield strength and tensile stress-strain behavior were then catalogued in accordance to the threshold temperature/dwelling time combinations that successfully achieved effective recrystallization. Results indicate that the dwelling time requires to accomplish full recrystallization varies with annealing temperature, showing higher the temperature shorter the dwelling time as expected. When specimens were fully annealed, they all show a common tensile behavioral feature of abrupt yielding from elastic to plastic state.

2. Advanced Characterization (ORNL)

Orientation imaging microscopy (OIM) was performed on a limited number of specimens as a result of intermittent computer problems, which terminated the large area OIM scans required for texture measurements. Measurements in the ND/RD plane were completed for both the surface and midplane of the as-rolled and as-annealed (900 C, 1 s) 0.08" 5754 materials. As a result of the inhomogeneous distribution of cube-textured areas in the as-rolled material, additional OIM measurements were made in the ND/TD plane at the surface and midplane of the as-rolled material.

The upgrade of the EBSP system at ORNL has been completed. A number of large EBSP data sets have been obtained for the CC5754 hot band in the RD-ND plane. These microstructures are being used as inputs to a Monte Carlo code to evolve the microstructure and texture during recrystalization.

4. Optimization Modeling (ORNL)

Preliminary calculations of thermodynamic equilibrium of phases in 5754 were carried out using Thermocalc™. The nominal composition of 5754 was in these calculations was Al-0.095Si-0.239Fe-0.028Cu-0.316Mn-2.854Mg-0.011Cr-0.001Zr. The thermodynamic calculations indicated that the Al6Mn precipitate is stable in this alloy system in the temperature range where earlier isothermal recrystallization experiments were carried out. The dissolution temperature of Al6Mn is calculated to be 860F. Therefore, it is possible that the dissolution of Al6Mn results in a drastic increase in the recrystallization kinetics at temperatures above 860F since the sub grains in the hot worked microstructure would no longer be pinned by the precipitates at these temperatures. Isothermal recrystallization experiments carried out at 880F indicate that the material is recrystallized extremely fast at this temperature and the time for 50% recrystallization deviates significantly from the ones calculated at lower temperatures. If these calculations are correct, then the exit temperature during in-line annealing should be greater than 880F in order to achieve recrystallization. Below this temperature, the amount of recrystallization that can be achieved in the time-scales planned in in-line annealing will be rather insignificant.

5. Isothermal Studies

The objectives of these studies are to develop a more fundamnetal understanding of the recrystallization kinetics of hot bands that cannot be obtained by continuous heating studies, and to provide input data for modeling recrystallization kinetics during continuous heating. All isothermal heating studies were carrried out in the Gleeble thermo-mechanical device. The Gleeble samples in the form of rectangular strips of 5" x 0.5" were rapidly heated to the peak temperature in about 1 second, held isothermally for the required amount of time and cooled rapidly to room temperature. In the last reporting period isothermal recrystallization kinetics for 750F, 800F, 850F, 900F and 950F were reported. However, the recrystallization kinetics at temperatures higher than 750F were so rapid, that the samples showed significant recrystallization on heating to the peak temperature. In order to ensure that the time to heat to the peak temperature was negligible compared to the recrystallization time, the experiments were carried out at lower temperatures of 690F and 720F. The recrystallized fraction was calculated as $[y_0 - y_t] / (y_0 - y_\infty]$ where y_0 is the yield stress of the as-received hot band, y_t is the yield stress after an isothermal hold of *t* seconds at temperature, and y_∞ is the yield stress of the fully recrystallized material.

The isothermal recrystallization kinetics at 690F, 720F and 750F. The data points are obtained from the Gleeble experiments, and the solid curves are obtained by fitting the data to the Johnson-Mehl-Avrami-Kolmogorov (JMAK) relationship given by

$$f = 1 - \exp\left(-kt^n\right)$$

where f is the fraction recrystallized at time t, k is atemperature-dependent constant, n is a roughly temperature-independent constant commonly known as the JMAK exponent. From the JMAK fit to the data points, the constants k and n are known for the three temperatures. From the fit equations, the time for 50% recrystallization, t_{50} were obtained. The apparent activation energy for recrystallization was calculated from the slope of the Arrhenius plot of log (t_{50}) versus $1/T$ where T is the recrystallization temperature in K.

Recrystalization kinetics under continuous heating: The objective here is to use the data obtained from the isothermal recrystalization studies to calculate the recrystalization kinetics under non-isothermal conditions, as in in-line annealing. For this purpose, the continuous heating curve is broken into a number of isothermal steps of known durations, the JMAK equation is applied to each time-temperature step, and a cumulative recrystallized volume fraction obtained at the end of the heating curve. The form of the JMAK equation used in this case is given by

$$f_{rex} = 1 - \exp\left[-\sum_{t=0}^{t=t} k(T)\Delta t^n\right]$$

where k(T) is given by $k(t) = k_0 \exp\left(-\frac{Q}{RT}\right)$

The constant k_0 is obtained from the known values of k and the activation energy Q obtained from the JMAK fit to the isothermal experimental data. The analytical model has been used to predict the re-crystallized volume fraction after a rapid heating to various peak temperatures in 1.0 second, in order to compare with the earlier IR heating experiments. A linear heating to the peak temperatures was assumed.

According to the model, an outlet hot band temperature in excess of 950F is required in order to fully re-crystallize the material on heating from 500F to the peak temperature in 1.0 s. This is in excellent agreement with the experimental data using IR heating. Figure 2 also shows that if the peak temperature is limited to 900F, a heating time of about 3.0 s is required to obtain complete recrystalization in the hot band. This may be applicable to higher gage hot bands with lower line speeds. Essentially, the model can handle any thermal cycle that includes the heating rate and the cooling rate in the coil. It may be possible to fully re-crystallize the material at a lower peak exit temperature than 950F if the material is coiled immediately, because the lower cooling rate experienced by the coiled material may promote recrystalization outside the in-line heater. The model is currently being used to include the recrystalization in the coil from knowledge of the cooling rate in the coil.

A Monte Carlo based recrystalization simulation code developed at ORNL was modified to receive OIM data as input. The code was further modified to receive grain boundary energy and mobility data for special boundaries based on existing molecular dynamics simulation results. The code was used with some of the OIM data obtained for the CC5754 hot band using the old EBSP system at ORNL. The data sets were generally rather small because of system limitations, although it was possible to generate a reasonably large dataset for a few RD-ND planes. Fig 1 shows the microstructure evolution for a data set roughly 600 x 600 in size. The green lines in figure 3 represent high angle boundaries with a misorientation greater than 15°, while the read areas represent low angle boundaries. Initial nucleation occurs in bands along the rolling direction. The nuclei grow and impinge at later stages of recrystalization, giving rise to an equiaxed grain structure. The simulated microstructures closely agree with those obtained using rapid heating.

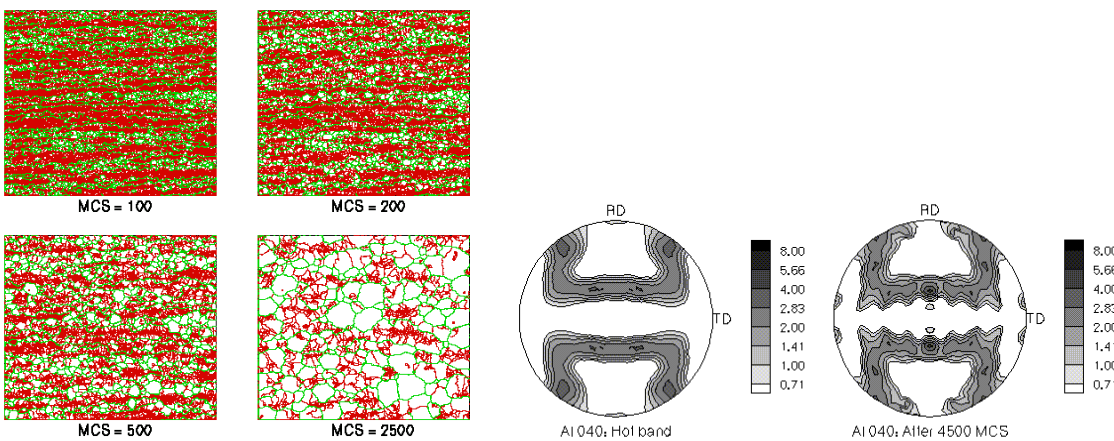

Fig 1. Evolution of the CC5754 hot band microstructure in the RD-ND plane during recrystalization (left) and texture evolution during recrystalization (right)

Recrystalization is followed by the formation of a weak cube texture. However, the current simulations are not able to capture the strong cube texture that is found experimentally. The texture evolution is very sensitive to the boundary properties, and current effort is focused on getting a closer match between simulated and experimental textures after recrystalization.

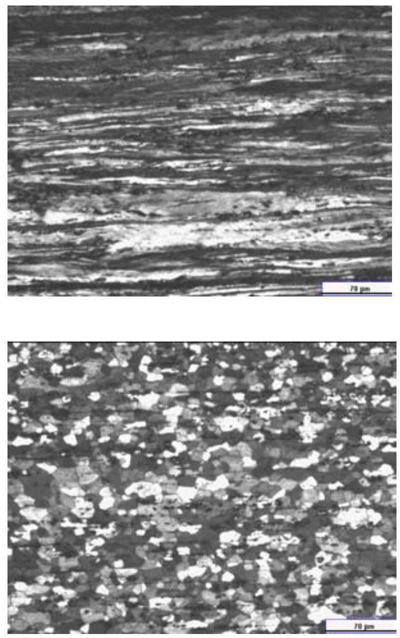

Fig 2. Microstructures of the CC hot band before (top) and after inline annealing at a furnace exit temperature of 650F (bottom).

Microstructure Modeling Studies (ORNL)

The Monte Carlo based microstructure and texture evolution tool developed previously was used to study the evolution of the cube and near-cube texture components during recrystallization. Large data sets obtained using the updated OIM facility at ORNL were used as inputs to these simulations. The evolution of the structure during recrystallization is shown in figure 3.

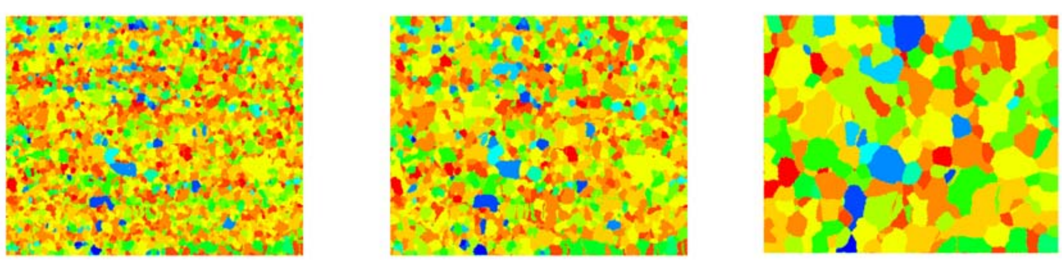

Fig 3. Microstructural evolution during recrystallization of CC hot band. The grains that are in various shades of blue correspond to the cube and near-cube texture components.

The cube and near-cube components grow during recrystallization, as shown in figure 3. The final volume fraction after recrystallization is about 5%. However, in experimental samples there is a variability in cube fraction from about 5% in certain location to a maximum of about 15% in other locations, as shown in figure 4.

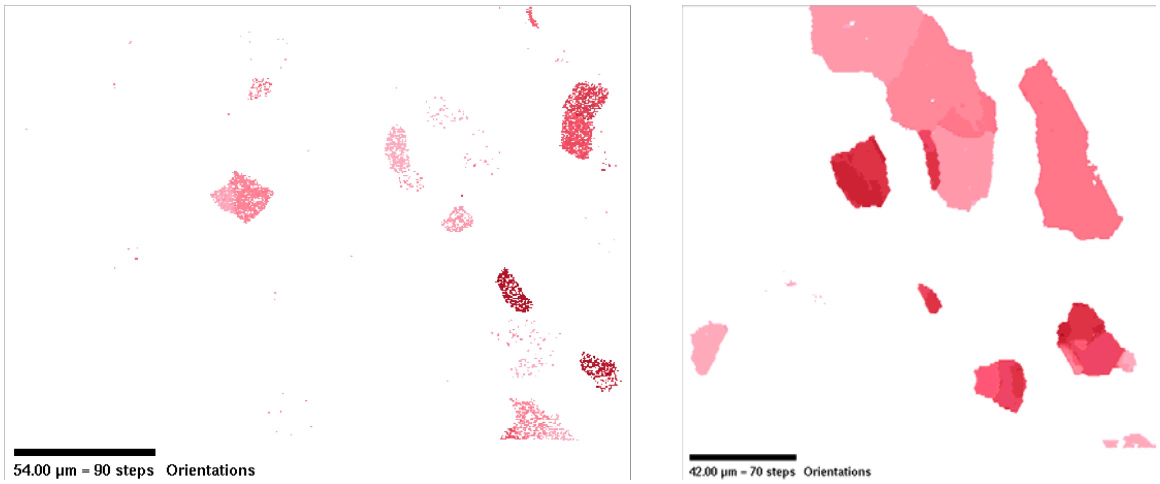

Fig 4. Grains that are in the cube or near-cube orientation after recrystallization of CC hot band. The two regions near the center line show the variability in cube fraction ranging from 5% (left) to 19% (right).

Plans for Next Quarter: ORNL effort will focus on further comparison of cube texture obtained at various locations in the recrystallized hot band with the simulated values to ensure that the simulations are accurately capturing the cube fraction. Also, efforts are underway to introduce time and temperature scaling in the Monte Carlo simulations. The final task is to package the computational tools such that they can be run in the future on personal computers in Secat and Commonwealth.

Patents: Nil.

Publications/Presentations: Nil.

Milestone Status Table:

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
1	In-line annealing facility		05/02	
2	Plant Trials		05/ 02	
3	Optimization Modeling	Ongoing		Will continue till the end of project
4	Material Characterization	Ongoing		Characterization of in-line annealed material will continue till end of project
5	Cost Evaluation	02/03		

Budget Data Excel spreadsheet attached